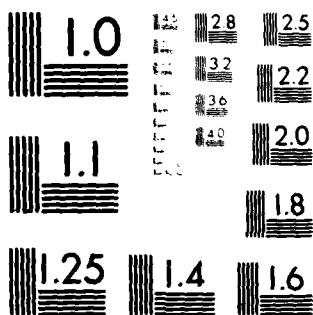


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OCULAR EFFECTS OF RELATIVELY 'EYE SAFE' LASERS.(U)
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OCULAR EFFECTS OF RELATIVELY "EYE SAFE" LASERS (U)

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Laser devices are an important part of current and future Army systems. Laser rangefinders, designators, communicators, and training devices are currently deployed or are in some stage of development. Most current laser rangefinders and designators, which enhance the effectiveness of the modern Army weapon systems, operate in the visible and near infrared region of the electromagnetic spectrum. The eye is particularly vulnerable in this wavelength region. The collimated laser radiation collected by the eye is transmitted by the ocular media with little attenuation and focused to a small spot on the sensory retina. The retinal irradiance is several orders of magnitude greater than that incident on the cornea; therefore, the total intraocular energy required to produce a retinal lesion is small. Lasers with output characteristic similar to those being fielded are capable of producing serious retinal injury at ranges that are tactically significant (1). The use of binoculars or magnifying optics increases the range at which these injuries can occur. Such devices cannot be used in training exercises without appropriate control restrictions or the use of protective devices. In some cases, training with the actual system in a realistic scenario is inhibited by these restrictions and troop proficiency may never be attained.

Ocular safety is particularly important for personnel using laser training devices where low power laser transmitters and sensitive receivers are used to evaluate the effectiveness of troops and tactics in two-way field exercises which simulate actual engagement scenarios. The MILES (Multiple Integrated Laser Engagement Simulator) program has resulted in the fabrication of laser transmitters configured to simulate several weapon systems. The gallium arsenide laser diodes used in these devices emit near 900 nm. The concern for eye safety when using this system stimulated careful bioeffects research (2) and a continual evaluation of maximum permissible exposures (MPE) given in AR 40-46 and TB MED 279 (3,4). If the emission from a laser system does not exceed the MPE as defined by TB MED 279 (3), then that system is a Class I system and can be referred to as "eye safe." To simulate weapon systems which are effective at longer

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ranges, lasers which emit more energy per pulse are required to offset losses due to atmospheric absorption and beam divergence. "Eye safe" lasers are desirable for these applications and for rangefinders and designators which can be used without restriction in training exercises. Laser systems operating beyond 1.4 μm have commonly been called "eye safe" and indeed, relative to lasers operating in the visible or near-infrared, the MPE for direct interbeam viewing is 2000 to 100,000 greater. However, only limited experimental biological effects data exist for wavelengths in this region of the spectrum.

In the spectral region from 1 to 3 μm , the outer ocular structures (cornea, aqueous, lens, vitreous) undergo the transition from highly transparent to essentially opaque. The absorption coefficient varies over 3 orders of magnitude (5). At 10.6 μm , where approximately 90% of the incident energy is absorbed in the first 70 μm of tissue, the corneal response at near threshold doses is confined to the corneal epithelium. Recovery from the insult occurs within 24 to 48 hours as observed by slit lamp microscopy (6,7). As the absorption decreases (in the 1-3 μm region), the incident energy is absorbed and is dissipated over a larger volume of tissue. The absorption of the incident radiation throughout a larger volume of tissue results in a higher threshold dose and therefore a reduced ocular hazard unless deeper structures such as the corneal endothelium or the crystalline lens are more sensitive to the radiation insult. Consequently, the wavelength dependence of the dose-response relationships can be compared to the wavelength dependence of the absorption of the ocular media.

The ocular effects of infrared lasers for specific exposure conditions have been described (2, 6-14). In this paper, experimental ocular dose-response data obtained at 1.732 μm are presented and compared to bioeffects data obtained at other wavelengths in this spectral region.

METHODS

An erbium laser operating at 1.732 μm was fabricated in our laboratory and operated in the long pulse mode. The 1/4 by 3 inch erbium rod (obtained from Sanders Associates, Inc., Nashua, NH) was inserted into an elliptical cavity and pumped by a linear flash lamp (EG&G Inc., FX-42C3, Salem, MA). Energy input to the lamp was approximately 425 Joules. The maximum energy in a single pulse at 1.732 μm was 200 mJ. The emission duration was 225 μs (FWHM) and reached complete extinction at 380 μs . The measured beam divergence was 3.0 milliradian. The laser exposure system is schematized in Figure 1. Because of the limited total output energy, a lens was used to focus the laser energy at the corneal plane. The small amount of energy (100 μJ) transmitted through the highly reflective mirror at the rear of the cavity was proportional to the energy measured at the cornea. Before exposure of the rhesus monkey's eyes, the ratio of the

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energy at the corneal plane to that at the reference detector was determined. Energy measurements were made with pyroelectric energy monitors (Laser Precision Corporation, Model RkP 335, Utica, NY). These detectors were calibrated with a disc calorimeter (Scientech Model 30-2002, Boulder, CO). Calibrated neutral density filters were placed in the beam to vary the energy per exposure. The point of intersection of the split beams from a helium neon laser was used to locate the corneal exposure plane and to facilitate selection of the corneal exposure site.

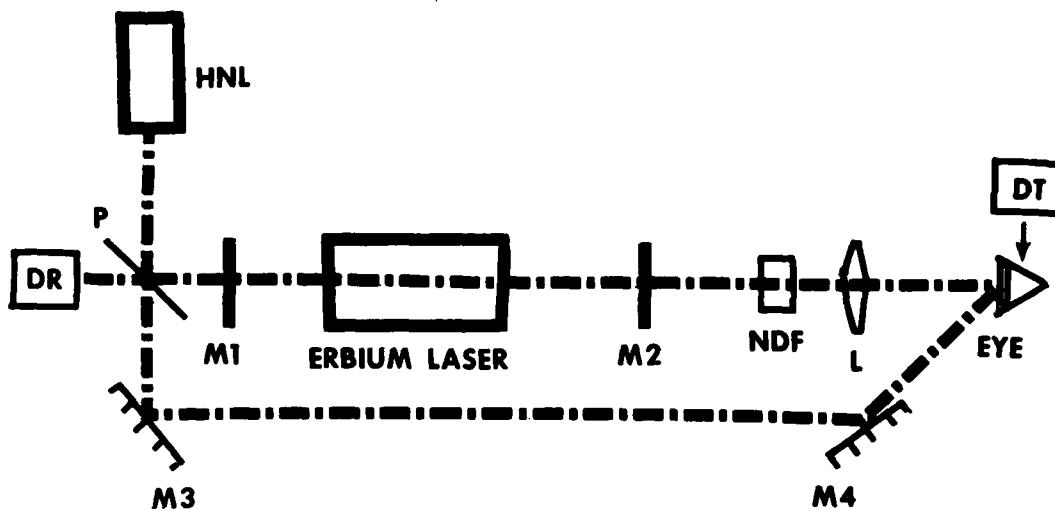


Figure 1. Erbium laser exposure system (emission wavelength = $1.732 \mu\text{m}$). DR - Reference detector, DT - Target detector, HNL - Helium neon alignment laser, NDF - Neutral density filter holder, M₁ to M₄ - mirrors, P - pellicle, L - lens.

Four lenses were used to obtain a range of corneal irradiance diameters. The corneal exposure plane was located in the experimentally determined focal plane a distance of f_p from the lens. The intensity profile of the beam and the effective beam diameter at the corneal plane were measured by two techniques. 1) By systematically reducing the energy per pulse and irradiating developed photographic paper, the relative intensity distribution was displayed. 2) Apertures with progressively decreasing diameters were placed at the exposure plane, and the total energy through each aperture was measured. The intensity profile at the focal plane was "approximately" gaussian and the reported beam diameters ($d_{1/e}$) are the diameters at the $1/e$ intensity points. The radiant exposure is the peak radiant exposure obtained by dividing the total incident energy by the area defined by the beam diameter ($d_{1/e}$).

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Rhesus monkeys (*Macaca mulatta*) were tranquilized with ketamine intramuscularly and anesthetized with pentobarbital sodium intravenously. The ocular pupils were dilated with one drop each of 2% cyclopentolate hydrochloride and 10% phenylephrine hydrochloride to facilitate biomicroscopic evaluation. The outer ocular structures (cornea, aqueous, lens, and vitreous) were carefully evaluated before and after exposure by use of the slit lamp biomicroscope. Body temperature during anesthesia was maintained with a thermal blanket. The eyelid was held open with a pediatric eye speculum and the cornea was gently irrigated with physiological saline to prevent drying. Six to nine exposures were placed in each cornea in an array of independent sites (Table 1). The dose was incrementally varied over a preselected range.

TABLE 1. CORNEAL ED₅₀s FOR SINGLE 225 μs EXPOSURES AT 1.732 μm.

f _p cm	d _{1/e} μm	ED ₅₀ (95% CI) J/cm ²	SLOPE J/cm ²	DOSE RANGE TESTED J/cm ²	No. ANIMALS/ EYES/ EXPOSURES
17.8	515	29 (27-31)	1.30	1.0-80	3/6/54
24.1	740	26 (23-29)	1.34	0.5-45	4/7/49
30.5	920	22 (20-23)	1.28	0.3-30	4/8/48
40.6	1200	>16*		14-16	1/2/8

* No ED₅₀ was determined for this condition because of the limited energy per pulse available from the laser.

The corneas were evaluated immediately and at 1 hour after the exposure. The response criterion was the appearance of a lesion at the exposure site as observed with the slit lamp biomicroscope. Other evaluations were made at 24 hr, 48 hr, 1 week and up to 6 months after exposure. The crystalline lens was also carefully evaluated. The effective dose for a 0.5 probability of producing an observable response (ED₅₀), the 95% confidence intervals about the ED₅₀, and the slopes of the regression lines through the experimental data (slope = ED₈₄/ED₅₀ = ED₅₀/ED₁₆) were determined by probit techniques (15).

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RESULTS

The ED₅₀'s for the production of a corneal lesion at 1.732 μm observed with the slit lamp biomicroscope and the exposure conditions are presented in Table 1. The ocular response for these exposure conditions was confined to the cornea. Corneal lesions generally involved the entire corneal thickness (Figure 2). Lesions near the ED₅₀ were smaller and less dense than those produced at 1.5 to 2.0 times the ED₅₀. No lesion was observed at 24 or 48 hours that was not observed at one hour. No lenticular effects were observed at one hour or in the four animals that were evaluated up to 6 months after exposure. Some corneal lesions observed at one hour were not observed at 48 hours. Over the limited range of exposure conditions, the ED₅₀ exhibits a dependence on the irradiance diameter (Figure 3). The radiant exposure required to produce a corneal lesion decreases as the irradiance diameter increases.

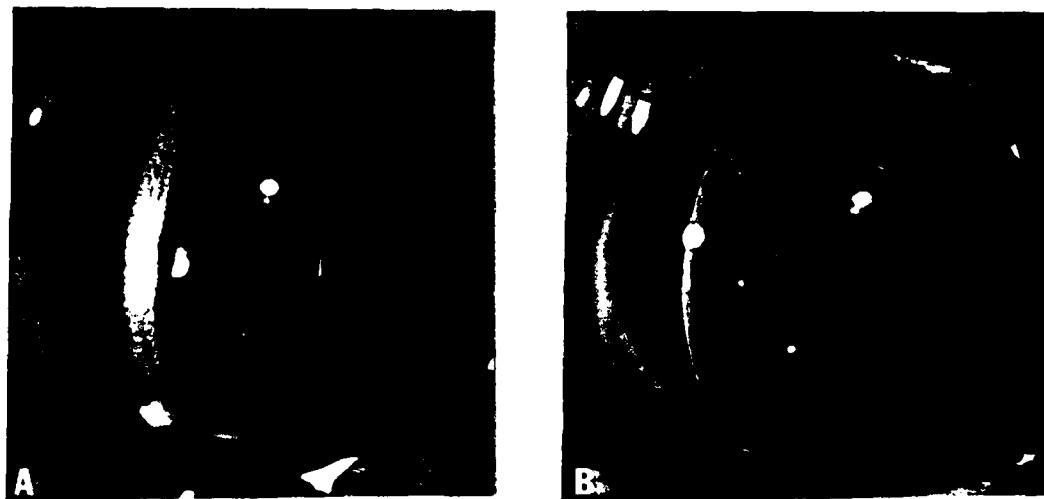


Figure 2. A. Slit lamp photograph of a corneal lesion one hour after exposure produced by an erbium laser operating at 1.732 μm (Corneal radiant exposure = 56 J/cm^2 , Exposure duration = 225 μs (FWHM), Incident beam diameter at the 1/e intensity points = 515 μm). B. Slit lamp photograph of the same lesion shown in A illuminated with a narrow slit of light showing that the lesion extends through the entire thickness of the cornea.

DISCUSSION

The corneal response resulting from exposure to infrared laser radiation is considered to be the result of a temperature elevation of the tissue. Sufficient energy is absorbed in a finite volume resulting in a localized temperature rise that produces a coagulation or opacification of

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the medium. Predictive thermal model calculations based on a localized elevation of temperature to a "threshold peak temperature" have been used to estimate the threshold dose required to produce a corneal lesion (16). These thermal model results are considered to be in good agreement with most experimental data published in this wavelength region. Experimental data of this and other experiments are given in Table 2. The ED₅₀'s for corneal injury at 1.732 μm are lower than the ED₅₀ obtained at the 1.33 μm and higher than those obtained for erbium laser radiation at 1.54 μm . This trend was anticipated based on the relative absorption of cornea at these three wavelengths. Corneal effects at 1.732 μm were similar to those produced at 1.33 μm and 1.54 μm in that the observed response extended throughout the full corneal thickness.

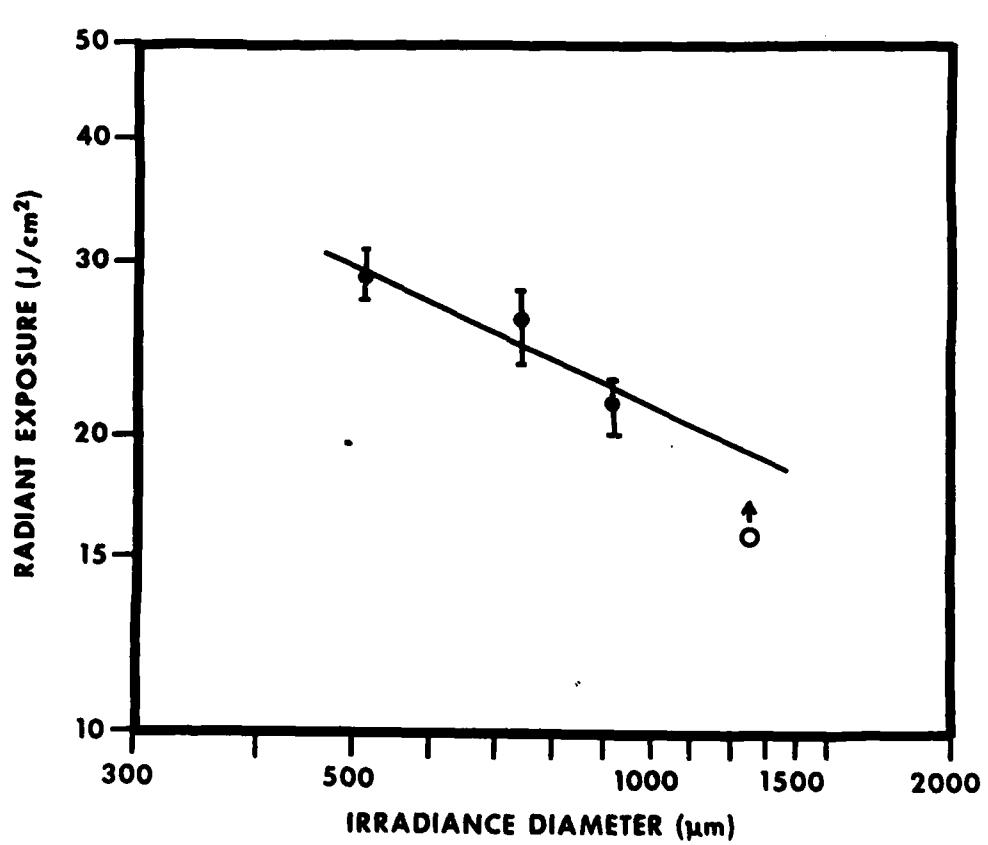


Figure 3. The ED₅₀ and 95% confidence interval about the ED₅₀ for the production of a corneal lesion as a function of the irradiance diameter of the incident beam ($d_{1/e}$). No corneal effect was observed for exposures made with the 1200 μm irradiance diameter (open circle with arrow).

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TABLE 2. CORNEAL DAMAGE THRESHOLDS FOR INFRARED LASER RADIATION

WAVELENGTH μm	EXPOSURE DURATION s	IRRADIANCE mm	CORNEAL DIAMETER cm ⁻¹	ED ₅₀ J/cm ²	REFERENCE
1.318-1.338 ^b	.25 ms	.40	2.28	45	9
1.41	25 ns	1.1	15.9	2.1-4.2	12
1.54	40 ns	1-2	9.03	4.7	13
1.54	50 ns	1	9.03	21.0	8
1.54	.93 ms	1	9.03	9.6	10
1.54	1.0 ms	1-2	9.03	7.2	13
1.732	.225 ms	.515	5.88	29.0	c
1.732	.225 ms	.740	5.88	26.0	c
1.732	.225 ms	.920	5.88	22.0	c
1.732	.225 ms	1.20	5.88	>16.	c
2.06	42 ns	.32	28.2	5.2	10
2.06	50 ns	.351	28.2	3.25	15
2.06	.10 ms	1.8	28.2	2.9	10
2.6-2.9 ^d	45 ns	0.82	>5000	.156	14
2.9	100 ns	10.0	12900	.006-.010 ^e	11
3.6-3.9 ^f	100 ns	.96	112-180	.377	14
10.6	1.4 ns	10.0	817	.013-.015 ^e	11
10.6	100 ns	2.1	817	0.35	2

a Corneal absorption coefficients from Reference 5 for wavelengths less than 2.1 μm. For wavelengths greater than 2.06 μm the absorption coefficient of water which approximates that of the cornea is tabulated.

b Multiline neodymium laser with 40% of the energy at 1.318 μm and 60% at 1.338 μm.

c This report.

d Multiline hydrogen fluoride laser.

e No ED₅₀'s was determined. The dose listed is the approximate threshold dose that an immediate response was observed.

f Multiline deuterium fluoride laser.

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The ED_{50} 's given in Table 2 are plotted in Figure 4 as a function of wavelength to exhibit the wavelength dependence of the damage threshold. Inherent to the wavelength dependence of the ED_{50} is the wavelength dependence of the ocular media absorption. The solid curve on Figure 4 is the depth at which 95% of the incident energy has been absorbed. The absorption coefficients of physiological saline which approximate that of the cornea and outer ocular media were used to calculate the 95% absorption depth. Let x_1 be the depth at which 95% of the incident radiation is absorbed. From Lambert's Law, $I/I_0 = e^{-ax_1}$, where I_0 is the incident intensity, I is the intensity transmitted through a thickness x_1 of medium with an absorption coefficient of a . By letting $I/I_0 = .05$ (i.e. 95% of incident energy absorbed), the depth or thickness x_1 can be calculated for a given absorption coefficient a . The volume in which the radiation is absorbed is equal to Ax_1 , where A is the cross sectional area of the incident beam. If Q is the incident energy, then the absorbed energy/ unit volume is Q/Ax_1 . Assuming the absorbed energy per unit volume required to produce corneal damage is independent of wavelength, therefore $Q/Ax_1 = k$ at the threshold dose where k is a constant. Consequently, the radiant exposure Q/A is directly proportional to the absorption depth or $Q/A = kx_1$. There is a direct correlation between the dose at threshold and the penetration depth (Figure 4).

Even though the exposure conditions (exposure duration, beam diameter), calibration, and observation criteria of different investigators were not identical for the experimental data subjected to this analysis, the wavelength dependence of the corneal ED_{50} 's is approximated by the shape of the absorption depth curve. Given identical experimental conditions across investigations and adjustment of absorption depth curve, a better fit to the experimental data may result. Doses required to produce an observable corneal response in the wavelength region between 1 and 2 μm were higher than those required at 2.8, 3.8, and 10.6 μm where absorption takes place within a much smaller volume. The corneal response of a near threshold exposure at the shorter infrared wavelengths involved the corneal stroma and did not exhibit the rapid repair as reported for the longer wavelengths where the threshold response only involved the corneal epithelium. The solid curve in Figure 4 supports that observation. Near threshold lesions at the shorter infrared wavelengths can be considered more severe since a long lasting stromal scar results.

For the exposure conditions evaluated to date at 1.732 μm , no retinal or lenticular effect has been observed; however, further evaluation for a collimated beam continues. The ED_{50} for an ophthalmoscopically visible retinal lesion was established for the 1.3 μm neodymium laser (2). The beam divergence was 2.3 mr, pulse duration was 650 μs and the corneal beam diameter was 5.5 mm. The total intraocular energy was 356 mJ resulting in a corneal radiant exposure of 1.5 J/cm^2 at the ED_{50} . If this energy were averaged over a 7 mm pupil, the corneal radiant exposure required to

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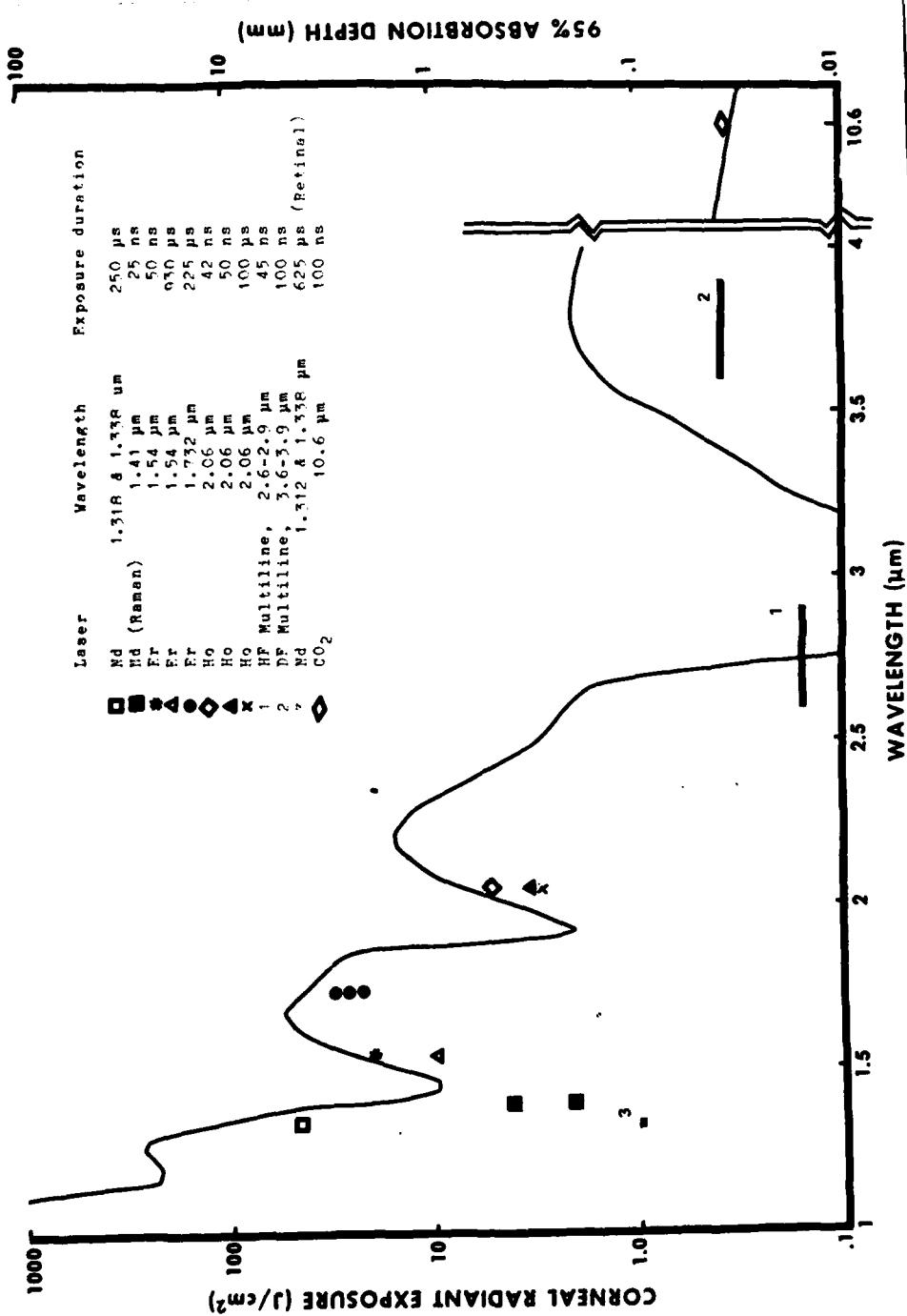


Figure 4. The ED₅₀s for the production of a corneal lesion for exposure conditions given in Table 2 as a function of wavelength. The solid curve is the depth (right hand axis) at which 95% of the incident energy is absorbed in physiological saline (the absorption properties of physiological saline approximate those of the outer ocular media). The data point at 3 is the ED₅₀ for production of a retinal lesion obtained at the 1.33 μm.

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produce retinal injury at $1.3 \mu\text{m}$ is 0.93 J/cm^2 . This value is also plotted in Figure 4. At $1.3 \mu\text{m}$, the corneal radiant exposure required to produce a retinal effect is much lower (Table 2) than that required to produce a corneal effect; nonetheless, the corneal radiant exposure required to produce a retinal response is 3 orders of magnitude greater than that required at $1.064 \mu\text{m}$ (2) and the MPEs for both lasers are identical (4).

The dependence of the corneal damage threshold on the irradiance diameter of the incident beam has not been described in previous investigations at any wavelength. Common to many of the investigations of the corneal effects in the infrared has been the necessity to focus the output energy on the cornea (8,9,10,12,13,15) because of the limited energy per pulse from typical laboratory laser devices operating in this wavelength region. Consequently corneal damage thresholds were obtained only for small irradiance diameters. For irradiance diameters from 500 to $1000 \mu\text{m}$, the radiant exposure required to produce a threshold lesion decreased as the beam diameter increased (Figure 2) for $1.732 \mu\text{m}$ laser radiation. Accidental exposures to infrared lasers will probably involve exposure of the entire cornea (irradiance diameters greater than 10 mm). Further evaluation of this dependence at other wavelengths in this region is required in order that the potential implication to the establishment of permissible exposure limits can be ascertained.

The MPEs for ocular exposure to wavelengths greater than $1.4 \mu\text{m}$ currently depend only on the exposure duration. These values have been based primarily on the dose-response relationships reported for carbon dioxide laser radiation ($10.6 \mu\text{m}$). No wavelength dependence of the MPE has been included in laser safety standards. The only exception is the elevated permissible exposures for the Q-switched erbium laser ($1.54 \mu\text{m}$) where experimental data (5) existed when these permissible exposure limits were established (3). The MPE for a single exposure less than $100 \mu\text{s}$ in duration is 10 mJ/cm^2 for laser radiation with wavelengths greater than $1.4 \mu\text{m}$ (1 J/cm^2 for $1.54 \mu\text{m}$ radiation). The MPE for ocular exposure to laser radiation at $1.732 \mu\text{m}$ or $2.06 \mu\text{m}$ is the same as the MPE at $10.6 \mu\text{m}$, even though the ED_{50} 's differ by a factor of 10 to 100. Although additional experimental dose-response data are needed in the 1 to $3 \mu\text{m}$ region for longer exposure durations, larger corneal irradiance diameters, and repetitive pulse conditions, a generalized wavelength correction to the MPE in the infrared spectral region is indicated by these experimental data. When compared to the MPEs for visible and near infrared radiation (the MPE ranges from 0.5 to $5 \mu\text{J/cm}^2$ for exposure durations less than $100 \mu\text{s}$), lasers operating beyond $1.4 \mu\text{m}$ are relatively "eye safe." Lasers operating in the IR-B region which emit 100 mJ per pulse could be used without stringent range control restrictions or protective devices. With current permissible exposure limits, a $1.54 \mu\text{m}$ laser would be desirable since the MPE is 100 times that for other systems such as holmium ($2.06 \mu\text{m}$) or erbium ($1.732 \mu\text{m}$).

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CONCLUSIONS

Ocular dose-response data obtained at 1.732 μm for exposure conditions examined thus far coupled with the other experimental data obtained in the wavelength region from 1.3 to 3.0 μm support consideration of including a wavelength dependence in the maximum permissible exposure. This wavelength dependence should be based on the relative absorption properties of the ocular media. Lasers which operate in this wavelength region offer a distinct advantage to the system developer from an "eye safety" standpoint.

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In conducting the research described in this report, the investigators adhered to the "Guide for the Care and Use of Laboratory Animals," as promulgated by the Committee on Revision of the Guide for Laboratory Animal Facilities and Care, Institute of Laboratory Animal Resources, National Academy of Sciences, National Research.

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